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Abstract

Errors arise when using conventional radar reflectivity, Z, to estimate rainfall rate, R, and these can be particularly severe during severe convective storms; the very events when accurate estimates are needed so that action can be taken to mitigate the effects of flooding. Concentration is on three problems associated with heavy rainfall: hail, attenuation and absolute calibration of the radar, and consider how polarisation radar parameters, differential reflectivity, Z_{DR}, and specific differential phase shift K_{DP}, might lead to their alleviation. It is essential to consider the fundamental limits to the accuracy with which these parameters can be estimated. If Z_{DR} can be measured to an accuracy of 0.2 dB, then it provides a measure of mean raindrop shape which is sufficiently precise to improve rainrate estimates. This can be achieved at S-band (10 cm), but seems very difficult for operational C-band (5 cm) radars; differential attenuation by the heavy rain introduces a negative bias into Z_{DR} which increases with range. However, the magnitude of this bias at C-band can then be used to correct for the total attenuation of Z. Differential phase, K_{DP}, has the advantage that it is a phase measurement and so is unaffected by attenuation. It only responds to the rainfall and is unaffected by the hail, but K_{DP} is a noisy parameter and is only useful for heavy rainfall above 30–60 mm hr^{-1}. Fortuitously, K_{DP} and Z_{DR} are not independent and one use of K_{DP} and Z_{DR} may well be to exploit this redundancy to identify rain areas as opposed to hail, and in rainfall to use the redundancy to provide an automatic calibration of the absolute reflectivity, Z, to 0.5 dB (12%). Finally, the noisy character of both Z_{DR} and K_{DP} together with the low level of the co-polar correlation coefficient provide the first reliable means of detecting and removing anomalous propagation which is a major operational problem for all weather radars.

Keywords: polarisation radar, rainfall calibration, attenuation, hail, anomalous propagation

Introduction

This article considers how radar estimates of rainfall in convective storms can be improved if, in addition to the conventional radar reflectivity, other parameters derived from the polarisation of the radar returns are available. Accurate radar measurements of rainfall are most important in heavy convective rain so that timely action can be taken– for example, in the real time control of sewage systems to avoid outflows into rivers and flooding of properties. In such conditions radar has the unique advantages of scanning rainfall rates over a large area with a rapid update time. For the past fifty years rainfall estimates (R) have been made based on the value of the radar reflectivity (Z) and there has been much debate about which of the many Z-R relationships it is appropriate to use. The difficulty arises because, for rain, $Z = \Sigma ND^6$, where N is the concentration and D the raindrop diameter, but $R \approx \Sigma N D^{3.7}$; typically an empirical relationship of the form $Z = 200 R^{1.6}$ is used. Typical errors for the instantaneous rain rate so derived are a factor of two. Much effort has been expended using rain gauges in real time to adjust and optimise the Z-R relationship, but recently it has become clear that the errors in R are not only due to changes in drop size distribution (Collier *et al.*, 1983; Austin, 1987; Joss and Waldvogel, 1990). In convective storms the following problems are probably the most severe:

1) AMBIGUITIES DUE TO HAIL

In convective storms the presence of hail gives rise to very large values of Z which can lead to unrealistic rainfall rates being estimated; to prevent this, sometimes the values of Z are clipped (typically at 55 dBZ, e.g. Mason, 1971). However, there are occasions when the high values of Z really do result from rainfall rates of (say) 200 mm hr^{-1}, and for the prediction of flash floods it is important to identify such regions.

2) ATTENUATION

Heavy rainfall can also cause appreciable attenuation leading to an underestimate of rainfall on the far side of a storm (e.g. Hitschfeld and Bordan, 1954). These problems are more important in Europe and Japan where C-band (5 cm) radars are in widespread use, but less so in the USA for the S-band (10 cm) NEXRAD radars.

3) ABSOLUTE CALIBRATION OF RADAR REFLECTIVITY

Much effort has been directed towards developing calibration techniques for Z, usually involving lengthy comparisons with rain gauges (e.g. Joss and Waldvogel, 1990; Joss and Lee, 1995). Sampling and representativity problems mean that what seems to be a straightforward and simple technique is in fact plagued with difficulties and leads to only limited success. This is because the rain gauge is a point measurement, whereas the radar beam is usually a volume of side several hundreds of metres. In addition the beam is some height above the gauge so wind drift can affect the calibration. A further complication is that the radar only samples above the gauge every five minutes or so, and in convective storms the rainfall rate can change appreciably during this time. If we want to compare the radar rainfall rate with the gauge to an accuracy of 10% every five minutes and the gauge registers a tip for every 0.2 mm of rain, then this is only possible for rather high rainfall rates above 24 mm hr^{-1}. Traditionally, the calibration of Z is provided by long term comparisons with rain gauges close to the radar.

Downdrafts of 8–10 m s^{-1} in convective storms will lead to an underestimate of rainfall from Z of up to 60% (Austin, 1987). This effect would be restricted to rather small regions of the storms and although it may be significant it is often ignored. Polarisation methods cannot help. The only means of identifying such regions would appear to be to use dual-Doppler radar coverage; but such coverage is unavailable from operational networks.

We shall consider observations made by the RAL Chilbolton 10 cm (S-band) radar and report recent observations which are typical of those made during the HYREX experiment; a more detailed comparison with raingauges can be found in Blackman and Illingworth (1997). This radar, with its 0.25° beamwidth and very high quality antenna, is able to transmit pulses alternately polarised in the vertical and horizontal and make extremely accurate polarisation measurements. Polarimetric techniques exploit the increasingly oblate shapes of larger raindrops to provide an estimate of raindrop size and then use this size information to remove some of the uncertainty in estimating rainfall rates from Z alone. They also exploit the fact that although hailstones may not be spherical, they generally tumble as they fall, and so make the same contribution to both the horizontally and vertically polarised radar returns.

Most operational radars in Europe and Japan operate at C-band with smaller 1° beamwidth antennas. The use of S-band for polarisation observations has two major advantages: firstly, we have Rayleigh scattering for nearly all meteorological targets, and secondly, there are normally negligible propagation or attenuation problems. Gate-by gate correction schemes (Hitschfeld and Bordan, 1954) are notoriously unstable and very sensitive to small calibration errors (Hildebrand, 1978). One approach at C-band is to use the polarisation parameters to correct for the appreciable attenuation which occurs in heavy rainfall.

In judging the efficacy of the various techniques we must bear in mind the dwell time and scanning implications. Conventional radar networks have products of estimated rainfall rate with a spatial resolution of about 2 km and an update time of 5 (or perhaps two and a half) minutes. This resolution means that in rapidly evolving storms the sampling places a limit in the accuracy of derived short-term precipitation totals even if the Z-R relationship is perfect. Fabry *et al.* (1994) analysed a reflectivity field with 250 m spatial resolution and 30 sec time interval and assumed the rainfall from a Z-R relationship was truth, and then simulated the degradation for 5 minute inferred rainfall accumulation totals when they undersampled the field in both space and time. For 2 km and 2 minutes the sampling errors are about 30%. We should aim at this accuracy with our polarisation techniques; a considerable advance over the factor of two from Z-R relationships. This is a best case; any variations in Z-R relationships or wind drift of the precipitation as it falls from the height of the radar beam to the ground (Collier, 1999) will mean that in practice the performance will be worse. There is nothing to be gained by improving upon this 30% accuracy unless it is possible to sample the field with higher resolution. If polarisation techniques require longer dwell times then they may sample less frequently and this could negate the increased accuracy of the instantaneous samples.

Definition of the polarisation parameters

We shall restrict our discussion to the use of linear polarisation in which the radar can transmit pulses which are polarised alternately in the horizontal and vertical, and can measure both the two co-polar returns Z_H, Z_v; and, if the radar is Dopplerised, the phase of the horizontally and vertically polarised returns, ϕ_h and ϕ_v. We shall consider two parameters: the differential reflectivity, Z_{DR}, and the specific differential phase shift, K_{DP}.

1) Z_{DR} – differential reflectivity (= 10 log (Z_H/Z_V)) is a measure of mean particle shape. Z_{DR} is particularly useful for rain, because small raindrops are spherical but larger ones become increasingly oblate. If we assume a simple exponential raindrop size distribution

$$N(D) = N_o \exp(-3.67\ D/D_o) \tag{1}$$

where D_o is the equivolumetric median drop diameter, then the value of D_o can be estimated from Z_{DR}. Once D_o is known then the value of N_o is fixed by the observed value of Z. An empirical Z-R relationship is equivalent to assuming we have a Marshall-Palmer distribution with N_o constant and equal to $8000\ m^{-3}\ mm^{-1}$, but the use of Z and Z_{DR} to fix both N_o and D_o, should result in more accurate rainfall estimates (Seliga and Bringi, 1976). In a subsequent section the required accuracy for measuring Z_{DR} and the effect of propagation on measurements at C-band are discussed.

Ice particles have a lower dielectric constant and so even if they are oblate they tend to have low values of Z_{DR}, particularly if, as is the case of snow, they are a low density mixture of air and ice. Once particles are wet the value of Z_{DR} increases, and so the bright band is associated with high values of Z_{DR}. In addition, in vigorous convection supercooled raindrops can be recognised by narrow vertical columns of positive Z_{DR} extending above the freezing level (e.g. Illingworth *et al.*, 1987).

2) K_{DP} – the specific differential phase arises because the propagation speed of the horizontally polarised radar wave through a region containing oblate raindrops is lower than the speed of the vertically polarised wave, and as a result the phase of the horizontal return, ϕ_h, lags progressively behind the phase of the vertical return, ϕ_v. As a result the differential phase, $\phi_{DP} = \phi_v - \phi_h$, normally increases monotonically with range and K_{DP}, the rate of change of ϕ_{DP} with range measured in °/km, is positive. The advantage of K_{DP} is that it is more linearly related to the rainfall rate than is Z. In addition, hail can dominate Z and lead to very high values of Z which are difficult to interpret in terms of a rainfall rate, but hail tumbles as it falls and tends to be more spherical so it gives no contribution to K_{DP}. K_{DP} can be quite difficult to measure as the phase shifts at S-band in light rain are small, but as K_{DP} scales with frequency the phase shifts are larger at C-band.

Raindrop shape model

Polarisation techniques rely on sensing drop shape and so it is important to use the correct drop shape model. A simple linear relationship between axial ratio, r, and drop diameter, D in mm, is in widespread use:

$$r = 1.03 - 0.062\ D \qquad (2)$$

for drops larger than 0.5 mm diameter with smaller drops assumed to be spherical. However, in some of the earliest observations Goddard *et al.* (1982) compared values of Z_{DR} computed from a raindrop disdrometer at the ground with those observed by a radar dwelling just above the disdrometer, and could only obtain agreement if they adjusted empirically the shape of drops smaller than 2.5 mm to be more spherical than given by Eqn. 1. They proposed (Goddard *et al.*, 1995) a new drop shape model:

$$r = 1.075 - 0.065\ D - 0.0036\ D^2 + 0.0004\ D^3 \qquad (3)$$

for drops larger than 1.1 mm with smaller drops again assumed spherical. Confirmation of such drop shapes is not simple. Measurements of raindrop shape close to the ground or *in-situ* with aircraft are not representative because of the atypically high stress or shear experienced by such drops, and it is only recently that careful experiments in long wind tunnels such as those carried out by Andsager *et al.* (1999, and references therein) have independently proposed the shapes in Eqn. 3. This independent confirmation of an empirical adjustment gives us confidence that the shapes of Eqn. (3) are indeed those occurring in natural rainfall.

Raindrop size spectra

To gauge the performance of polarisation techniques in improving rainfall estimates by removing some of the drop size spectrum uncertainty implicit in using a simple Z-R relationship we need to know the variability of naturally occurring raindrop size spectra. It is known that the simple exponential representation suggested by Marshall-Palmer is too simple and that a normalised gamma function (Illingworth and Blackman, 1999) of the form

$$N(D) = c\ N_L\ D^{\mu} \exp(-(3.67 + \mu)D/D_o) \qquad (4)$$

is more appropriate, where μ is the index of the gamma function, D_o the equivolumetric median drop diameter, c a normalisation constant, and N_L a concentration. If Eqn. 4 is not normalised then the concentration is correlated with μ and varies over 25 orders of magnitude, but normalisation with respect to liquid water content leads to a value of N_L which is independent of μ and better reflects the true drop concentration (Illingworth and Johnson, 1999). For $\mu = 0$ Eqn. 4 reduces to the simple exponential, but for positive values of μ the spectrum is increasingly monodispersed with fewer very large or very small drops than predicted by the simple exponential. Kozu and Nakamura (1991) equated the sixth, fourth and third moments of observed raindrop size distributions to the appropriately weighted integral expression from a non-normalised version of Eqn. 4 and so deduced values of μ, D_o and N_L in naturally occurring rainfall. Values of μ ranged from 0 to 15 with the mean value of about 5 or 6. Figure 1 shows the results (Illingworth and Johnson, 1999) of fitting the 1250 naturally occurring raindrop spectra during the month of July 1988 (chosen because of its heavy rain rates) at Chilbolton and shows that the mean value of μ is about 6 in natural rain but can vary between 0 and 15. The mean value of the normalised concentration $\log(N_L)$ is about 3.93, very close to the equivalent Marshall-Palmer value of $\log(8000\ m^{-3}\ mm^{-1})$. The standard deviation of N_L is about a factor of three

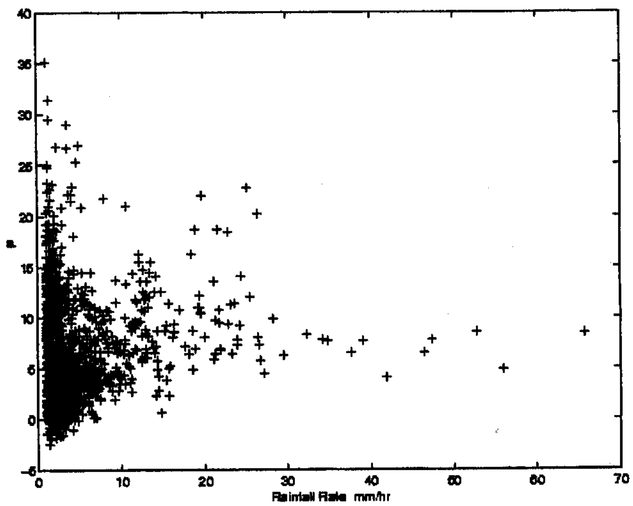

Fig. 1. *Values of μ as a function of rainfall rate when natural raindrop spectra observed at Chilbolton are fitted to the gamma function (Eqn. 4).*

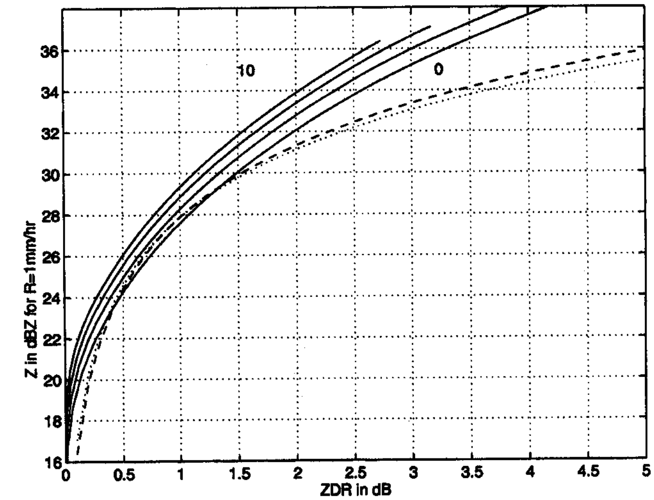

Fig. 2. *Values of Z which would give a rain-rate of 1 mm hr^{-1} as a function of Z_{DR} at S-band for raindrop spectra with μ = 0, 2, 5, and 10 (solid lines) in Eqn. 4. The actual rain-rate scales with the observed Z. Dashed line from Chandrasekar and Bringi (1988) and dotted line from Chandrasekar et al. (1990) using 'linear' drop shapes.*

which is consistent with the 'factor of two' error for instantaneous rainrates derived from a simple Z-R relationship. This range of μ and N_L will be used in predicting the performance of the polarisation parameters in improving rainfall estimates.

Differential reflectivity, Z_{DR}

The observed values of differential reflectivity in rainfall provide an estimate of D_o in Eqn. 4 which is independent of drop concentration. The value of Z then scales with concentration or rainfall rate. In Fig. 2 we have plotted the value of Z which would give a rainfall rate of 1 mm hr^{-1} as a function of observed Z_{DR} for the range of μ in natural rain with spectra given by Eqn. 4 and for the rain drop shapes of Eqn. 3 at S-band; the C-band curves differ only slightly. The four solid curves are the values of Z for four different values of μ as a function of the observed Z_{DR} for 1 mm hr^{-1} rainfall rate. Because both rainfall rate and reflectivity (Z–expressed in linear units) scale linearly with drop concentration, the factor by which the observed value of Z exceeds the value of Z in Fig. 2 is the factor by which the actual rainfall rate exceeds 1 mm hr^{-1}.

From the separation of the four solid curves in Fig. 2 we can see that the variability of μ in naturally occurring rain leads to an uncertainty in rainfall rate for a given Z and Z_{DR} of about $\pm$1 dB or $\pm$25%, and that this absolute limit to the accuracy of rainrates using the Z/Z_{DR} technique arises from the variability of the shape of naturally occurring raindrop size spectra. The slope of the solid lines in Fig. 2 shows that to achieve this 1 dB accuracy in the value of Z for a given rainfall rate we need to estimate Z_{DR} with an accuracy of $\pm$0.2 dB. Z_H and Z_V are both fluctuating but because they are highly correlated it is possible to estimate Z_{DR} to a higher accuracy than Z itself, and an accuracy of $\pm$0.2 dB requires about sixty independent samples of Z (Bringi *et al.*, 1983) providing the correlation coefficient of Z_H and Z_V is over 0.98 as is usually the case in rain. The dwell time required is of course a function of the Doppler width of the target but for ten independent samples is about 150 msecs at C-band and 300 msecs at S-band. The requirement for 60 independent samples can be met by averaging over six adjacent gates, each typically 150 m long (1 μsec transmitted pulse) and so provides a satisfactory spatial resolution of 1 km. For a C-band radar with a beamwidth of 1° this implies a scan rate of 6° sec^{-1} so that a sequence of five PPIs at different elevations could be accomplished every five minutes.

Goddard and Cherry (1984) have demonstrated that if these conditions are fulfilled then it is possible to derive improved rainfall rates using both Z and Z_{DR} at S-band. Figure 3 is a ray profile of Z and Z_{DR} taken through a heavy rain shower at Chilbolton with values averaged over 4 adjacent 75 m gates for a 210 msec dwell. The values of Z and Z_{DR} are correlated as would be expected from Fig. 2, but Fig. 2 predicts that once Z falls below 20 dBZ, then Z_{DR} should be essentially 0 dB. Analysis of Fig. 3 and other data from Chilbolton confirms that, for Z below 20 dBZ, the mean value of Z_{DR} is close to 0 dB and the standard deviation is about 0.15 dB and the performance of the radar is as predicted by theory of Bringi *et al.*, 1983.

Other factors may lead to this 25% accuracy not being achieved. Firstly, the absolute calibration of Z must be correct to within 25%. The rainfall estimate scales linearly with Z, so any error in Z feeds directly through to the rainfall rate. Secondly, hail mixed with rain can lead to a reduction in Z_{DR} of the rain alone. Hail tends to tumble as it falls and so has a zero or slightly positive value of Z_{DR} and so

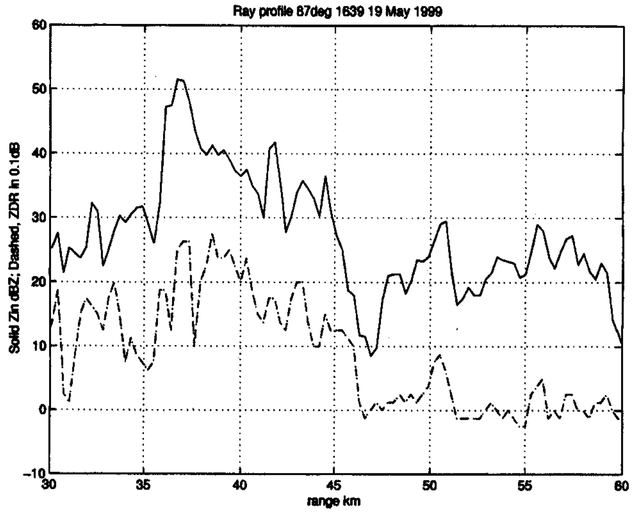

Fig. 3. *A ray profile of Z and Z_{DR} observed through heavy rain at Chilbolton at S-band obtained every 300 m by averaging over four 75 m gates for a dwell time of 210 msecs.*

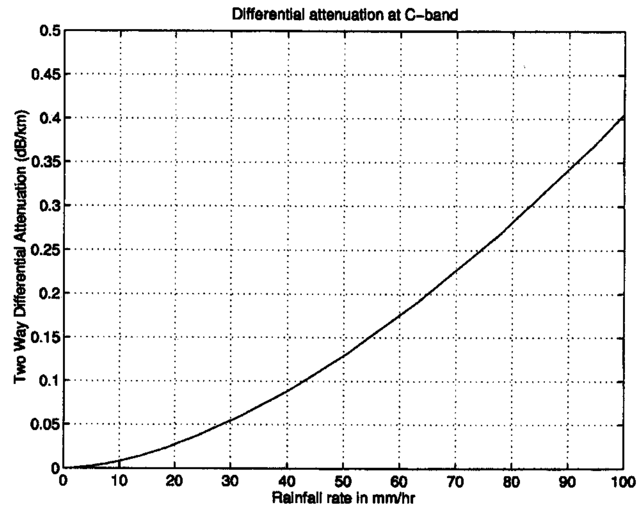

Fig. 4. *Differential attenuation at C-band as a function of rainfall rate for Marshall-Palmer rain at 0 °C.*

will tend to reduce the observed Z_{DR} but makes a large contribution to Z; if this reduced value is used in Fig. 2 then spuriously high rainfall rates can be predicted. From the Z_{DR} observation alone it is impossible to know when this hail contamination is occurring. Thirdly, the 'wrong' choice of raindrop shape model can lead to different predictions of rainfall rates from Z and Z_{DR} which differ by up to 3 dB. The solid lines in Fig. 2 are for the 'new' drop shapes of Eqn. 3, whereas the dashed one (Chandrasekar and Bringi, 1988) and the dotted one (Chandrasekar *et al.*, 1990) use the linear shapes of Eqn. 2. As indicated above Eqn. 3 is believed to be more realistic. Fourthly, although the narrow beamwidth Chilbolton radar yields Z_{DR} data with a noise level agreeing with theoretical predictions, much published data has a noisier Z_{DR} than would be expected. This is probably due to the broader beam antenna, which, in the presence of reflectivity gradients, will receive a significant fraction of the power through sidelobes which are mismatched in their polarisation characteristics. Herzegh and Carbone (1984) report spurious values of Z_{DR} of up to 10 dB in low reflectivity regions adjacent to intense echoes. For any radar measuring Z_{DR} it is important to examine the statistics of the data to ensure that accurate estimates are being obtained.

A much more severe problem arises at C-band. As the radar beam penetrates heavy rain, the large oblate raindrops attenuate the horizontally polarised beam more than the vertical one, and that this differential attenuation leads to increasingly negative values of Z_{DR} with range; values as low as -5dB have been observed at C-band (Upton and Fernandez-Duran, 1999). Such attenuation must be corrected to better than ± 0.2 dB if the values of Z_{DR} are to be used quantitatively. The scale of the problem is evident from Fig. 4 which displays the computed value of differential attenuation as a function of rainfall rate at C-band for Marshall-Palmer rain and demonstrates that the limit of acceptable differential attenuation is reached for only 1 km for rain at 65 mm hr^{-1} and 2 km at 40 mm hr^{-1}.

Bringi *et al.* (1990) have proposed that attenuation (A_h in dB km^{-1}) and the differential attenuation ($A_h - A_v$ in dB km^{-1}) can be uniquely estimated from the value of differential phase shift (K_{DP} in ° km^{-1}) at either S-band or C-band. This has been the basis of many correction schemes. Smyth and Illingworth (1998) pointed out that the assumption of linearity between phase shift and attenuation only holds for rain when the equivolumetric drop diameters $D_o < 2.5$ mm (or a differential reflectivity, $Z_{DR} < 3$ dB), and that in most attenuation events Z_{DR} is much above this value. When $D_o > 2.5$ mm then even at S-band there is more attenuation for a given phase shift than is the case for smaller raindrops, and observations at S-band show that simple relationship predicted by Bringi *et al.* (1990) breaks down.

The difficulty of deriving attenuation from differential phase shift, as proposed by Bringi *et al.* (1990), arises because the former depends upon the imaginary part of the forward scattering amplitude whilst the latter depends upon the real part. The real and imaginary parts have a different variation with temperature and raindrop size. This led Smyth and Illingworth (1998) to suggest that the total attenuation could be derived from the total differential attenuation, $A_h - A_v$, because both depend upon the imaginary part of the scattering amplitude. $A_h - A_v$, being estimated from the magnitude of the negative Z_{DR} behind the intense echo where Z is below 15 dBZ and one would expect Z_{DR} to be very close to 0 dB. It turns out that at C-band the relationship between attenuation and $A_h - A_v$, is not sensitive to the value of μ in the drop size spectrum or the temperature. For example, an $A_h - A_v$ of 3 dB can correspond to an A_h of 7.8 dB at 20°C which only rises to 9 dB at 0°C.

The conclusion is that at C-band differential attenuation in heavy rain introduces such a bias into Z_{DR} that it cannot be used to estimate drop sizes and so improve rainfall estimates. However, this differential attenuation, does produce a very obvious region of negative Z_{DR} extending like a searchlight (Upton and Fernandez-Duran, 1999) behind high intensity echoes. These regions of negative Z_{DR} are a signature that attenuation of Z is also occurring, and it is recommended that the negative magnitude of Z_{DR} be used to correct for the Z attenuation. Smyth and Illingworth (1998) suggested that the total attenuation derived from the negative value of Z_{DR} be distributed along the path in proportion to the differential phase shift observed along the path.

K_{DP}, Specific differential phase shift

This technique is very attractive. In theory the measurement is simple as it involves measuring and comparing the phase of the returns at horizontal and vertical polarisation to find $\phi_{DP} = \phi_v - \phi_h$, and then differentiating ϕ_{DP} with range to give K_{DP} in $°\,km^{-1}$. For rain with a Marshall-Palmer drop size distribution and for 'linear' raindrop shapes (Eqn. 2) Sachidananda and Zrnic (1986) proposed the following relationship at S-band

$$R = 37.1\,K_{DP}^{0.866} \qquad (5)$$

or about $1°\,km^{-1}$ (one-way) for a rain rate of 37 mm hr^{-1}. At C-band one way relationships such as

$$R = 16.03\,K_{DP}^{0.95} \qquad (6)$$

have been proposed (Aydin and Giridhar, 1991; Scarchilli *et al.*, 1993). If the 'new' drop shapes of Eqn. 3 are used then these equations are slightly, but significantly, changed; at S-band for a K_{DP} of $1°\,km^{-1}$ the rainfall is increased by about 25%.

The advantages of the technique are as follows (Blackman and Illingworth, 1995);

1) No need for calibration.
The measurement of phase is unaffected by calibration problems
2) Immune to attenuation.
The phase measurement is not affected by attenuation.
3) Linear relationship with R.
The value of K_{DP} is nearly linearly related to R and so should be less affected by change in the raindrop size spectra than are Z-R relationships.
4) Immune to hail contamination.
Hail tumbles as it falls and so should have no effect on K_{DP} which should only respond to the raindrop component: in contrast hail can dominate the radar reflectivity and when conventional Z-R relationships are used this can lead to unrealistically high values of inferred rainfall rates. Hail also depresses the observed value of Z_{DR}. English *et al.* (1991) and others have demonstrated the improved rainfall estimates using K_{DP} in the presence of hail.
5) Use of partially blocked beams
It is possible to make differential phase and therefore K_{DP} measurements in lower beams which are partially blocked and whose Z values are considerably attenuated. Accordingly, with K_{DP} it may be possible to extend the range of measurements by using very low elevation beams which will remain in the rain out to greater distances. However, the phase measurement is very sensitive to small amounts of ground clutter. If the amplitude of the ground clutter signal is 10% of the value for the precipitation then it will introduce a phase noise of about 5° and prevent useful phase measurements, but this ground clutter will have an intensity of only 1% of (or 20 dB below) the precipitation value and so the value of Z will be virtually unaffected.
6) Integrated rainfall over a catchment.
The total differential phase shift along the path, Ψ_{DP}, is related quite closely to the total integrated rainfall through the near linearity of Eqns. 5 and 6. Accordingly, the total phase shift recorded across a catchment may provide an integrated rainrate across the catchment.
7) Recognition of ground clutter and anaprop.
Ground clutter and anaprop have random phase differences in H and V and so can be easily recognised by their noisy ϕ_{DP} ray profile (Ryzhkov and Zrnic, 1998b) which could be used together with the low level of co-polar correlation (ρ_{HV}) of the time series of the Z_H and Z_V returns from these targets (Caylor and Illingworth, 1992).

The major difficulty in practice is that the differential phase changes are both small and noisy. Differential phase is measured using sequential pulses transmitted with alternate horizontal and vertical polarisation, but the phase is continually changing due to the mean Doppler velocity of the targets and so some interpolation is required to estimate the correct ϕ_{DP}. The finite Doppler width means that the phase change is no longer linear and so the interpolation introduces some error. Ryzhkov and Zrnic (1998a) show that the expected standard deviation of the ϕ_{DP} estimate is a function of the normalised spectrum width and the number of transmitted samples, falling to about 1° for a normalised width of 0.1 and 60 pulse pairs. Figure 5 shows an example of a ray profile of ϕ_{DP} estimated for every fourth gate for 64 pulse pairs estimated by the Chilbolton data for the same ray as in Fig. 3; the total phase shift is over 30° and beyond 45 km ϕ_{DP} is essentially constant with a standard deviation of 1.5°.

Several stages are then involved in calculating the rainfall rate. Firstly, K_{DP} is estimated from a linear fit through the ϕ_{DP} profile, then several adjacent rays can be averaged

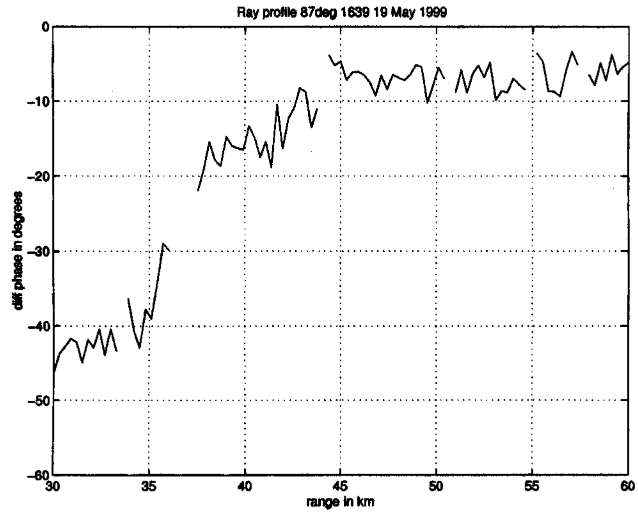

Fig. 5. *A ray profile of ϕ_{DP} observed through the same heavy rain as in Fig. 3. Dwell time is 210 msec, but only one 75 m gate is used every 300 m. The standard deviation of ϕ_{DP} is over the range 45–60 km is 1.5°.*

together. Blackman and Illingworth (1997) considered the accuracy of the rainfall rate that could be estimated from ϕ_{DP} data with 150m gate length, a standard deviation of 1.5°, and a 1° beamwidth scanning at 5° s^{-1} over a square region as a function of range. These scan rates and resolution are those required by operational radars. A 25% error in retrieved rainfall rate was achieved at S-band for a 2.4 km box at a range of 75 km provided the rainfall rate was above 30 mm hr^{-1}, and for C-band the equivalent figure was 18 mm hr^{-1}. These accuracies scale linearly with the standard deviation of the ϕ_{DP} estimate. At a range of 60 km a 1° beamwidth radar would have a resolution for Z of about 1 km; at this range the accuracy of rainfall from K_{DP} as discussed above but for a 1.2 km box would be 66 and 43 mm hr^{-1} at S and C-band respectively.

Ryzhkov and Zrnic (1995) cite a typical standard deviation of ϕ_{DP} at S-band of 3°, and Hubbert *et al.* (1993) quote a similar figure for the C-band radar at DLR as do Keenan *et al.* (1998). These figures suggest that a 25% error estimate of rainfall over a 2.4 km box at a range of 75 km is only possible if the rainfall rate exceeds 60 mm hr^{-1} at S-band and 36 mm hr^{-1} at C-band. These are severe restrictions, and so Ryzkhov and Zrnic (1996) suggest averaging over 4 km in heavy rain and 10 km in light rain, but the penalty in terms of the loss of spatial resolution is severe.

It appears that with the larger sized antennae the loss of performance is associated with gradients of reflectivity across the radar beam (Ryzhkov and Zrnic, 1998a). In addition at C-band there can be difficulties associated with differential phase on backscatter given a transient local maximum on the ϕ_{DP} profile superposed on the propagation effects which should be monotonically increasing with range. The differential phase on backscatter occurs when the hydrometeors are large enough to undergo Mie scattering as would be the case for hail. Spatial filtering is usually recommended to remove these transient affects, although one can never be quite sure how widespread is the region affected and there is a loss of spatial resolution.

In summary K_{DP} has many advantages and if ϕ_{DP} can be estimated accurately enough then it can be used to estimate high rainfall rates reliably even in the presence of hail. However, the dwell times in an operational environment at C-band limit its use to rainfall rates above 18 mm hr^{-1} if we seek 2.4 km resolution at a range of 75 km but antenna imperfections may well restrict its use to rainrates of twice this value.

Techniques combining K_{DP} with Z_{DR}–autocalibration of Z

Ryzhkov and Zrnic (1996) and other workers have proposed relationships of the form:

$$R = 52\,K_{DP}{}^{0.96} Z_{DR}{}^{-0.447} \tag{7}$$

which combine both Z_{DR} and K_{DP} to produce an improved estimate of rainfall. Such formulae are based on cycling raindrop spectra over an expected range of parameters and using the linear 'drop shapes' of Eqn. 2. Several comments are in order. Firstly, the Z information is not being used at all, and secondly if hail is present the Z_{DR} value will not be the true value for the rain. More importantly, as discussed below, the values of Z_{DR} and K_{DP} in rain are not independent so that Eqn. 7 cannot provide additional information.

Goddard *et al.* (1994) using the 'new' drop shapes of Eqn. 3 showed that Z_{DR} and K_{DP} in rainfall are not independent, and that, fortuitously, in rain K_{DP}/Z is a unique function of Z_{DR} which is independent of the μ of the rainfall as shown in Fig. 6. They suggested that this redundancy should be exploited to provide an absolute calibration of Z as indicated in Fig. 7. The observed value of Z and Z_{DR} at each gate are used to predict the value of K_{DP} at each gate, and so the predicted phase shift at each gate can be calculated and added up to give thetheoretical total phase shift along the ray, Ψ_{DP}. This total phase shift can be compared with the observed total phase shift, and the value of Z scaled until the computed value agrees with the measured value. The advantage of this technique is that the total phase shift is a robust observation derived from averaging the two almost constant values of ϕ_{DP} before and after the heavy rain. Even after filtering the observed ϕ_{DP} ray profile is noisy, so differentiating gives a K_{DP} estimate which is even noisier, but in this method the observed total phase shift Ψ_{DP} is used rather than the noisy K_{DP} estimate. As shown in the figure it is possible to fix the calibration of Z to better than 0.5 dB or 12% every time there is heavy rainfall. At C-band this calibration technique can also be used, providing the values of Z and Z_{DR} are not affected by attenuation. The

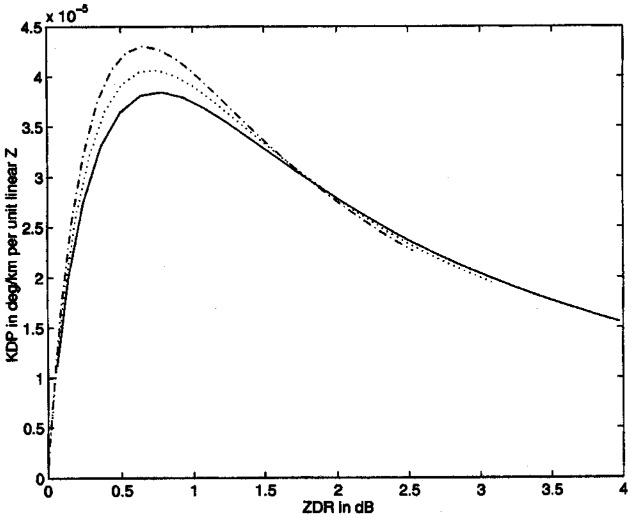

Fig. 6. *Autocalibration technique for Z at S-band. Values of K_{DP}/Z as a function of Z_{DR} for 'new' raindrop shapes for different values of μ in the gamma function. Solid line $\mu = 0$, dotted line $\mu = 2$, dash-dot $\mu = 5$.*

calibration thus obtained should then be valid for the attenuated rays until there is some drift in the hardware.

Smyth *et al.* (1999) took this argument one stage further, suggesting that the best technique in heavy convective rain is to monitor continually the consistency of Z and Z_{DR} and the observed value of total phase shift, Ψ_{DP}, along each ray. Consistency implies the precipitation type is rain so the best approach is to use Z and Z_{DR} at each gate to derive rainfall rates accurate to 25%. Inconsistency implies hail and then R-KDP equations of the form of (5) and (6) should be used.

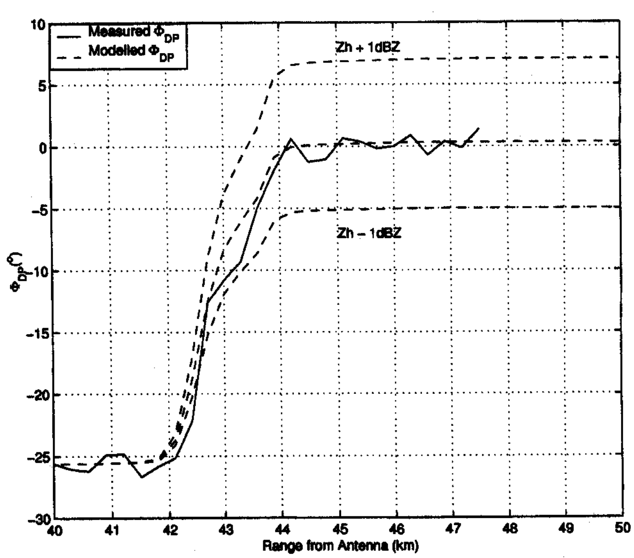

Fig. 7. *Example of autocalibration. Different calibrations of Z lead to three different traces for Ψ_{DP}. Comparison with the observed Ψ_{DP} in rain fixes the calibration of Z to 0.5 dB (10%).*

Conclusions

Considerable care is needed when implementing a polarisation radar technique for improving rainfall rate estimates in convective storms. The following applications should be valuable.

1) Automatic calibration of Z.
   At both S and C-band then the consistency of Z and Z_{DR} and the observed value of total phase shift, Ψ_{DP}, along each ray can provide an absolute calibration of Z to within 12%. At C-band rays must be chosen where attenuation affects are negligible. This appears to be the most accurate and reliable method of providing continuous calibration of the reflectivity measurements.
2) Correction of attenuation at C-band.
   At C-band attenuation is a major problem. Such regions can be recognised by the cone of negative Z_{DR} spreading out behind them. The magnitude of this negative Z_{DR} cone can be used to correct the attenuated Z values
3) Recognition of hail at S-band.
   At S band when the consistency of Z and Z_{DR} and the observed value of total phase shift, Ψ_{DP}, breaks down then hail is present, and rainfall rate should be derived from the differential phase (Eqns. 5 and 6). At C-band this method fails due to differential attenuation affecting the values of Z and Z_{DR}.
4) More accurate rainfall rate at S-band.
   When the consistency of Z and Z_{DR} and the observed value of total phase shift, Ψ_{DP}, indicates rain then the values of Z and Z_{DR} can be used to provide rainfall rates which should be accurate to 25%, providing Z_{DR} can be estimated to better than 0.2 dB and Z is calibrated to within 25%. This is an improvement over the 'factor of two' from the conventional Z-R relationships in use today.
5) Recognition of Anomalous Propagation.
   These spurious echoes are a major operational problem for all weather radars. They can be recognised easily by the large gate to gate variability of both differential phase and differential reflectivity together with the low value of the co-polar correlation and this should provide the first reliable means of detecting and removing anomalous propagation.

In summary, polarisation techniques can play an important role in operational C-band radars, by providing an automatic self calibration for the Z measurement, by recognising and correcting attenuation in heavy rainfall, and by unambiguously identifying regions of anomalous propagation.

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